

Variability in the Milky Way: Contact binaries as diagnostic tools

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Abstract. We used the 50 cm Binocular Network (50BiN) telescope at Delingha Station (Qinghai Province) of Purple Mountain Observatory (Chinese Academy of Sciences) to obtain simultaneous *V*- and *R*-band observations of the old open cluster NGC 188. Our aim was a search for populations of variable stars. We derived light-curve solutions for six W Ursae Majoris (W UMa) eclipsing-binary systems and estimated their orbital parameters. The resulting distance to the W UMas is independent of the physical characteristics of the host cluster. We next determined the current best period–luminosity relations for contact binaries (CBs; scatter $\sigma < 0.10$ mag). We conclude that CBs can be used as distance tracers with better than 5% uncertainty. We apply our new relations to the 102 CBs in the Large Magellanic Cloud, which yields a distance modulus of $(m - M_V)_0 = 18.41 \pm 0.20$ mag.

1. Contact binary systems

Contact binaries (CBs) are binary systems where both stellar components overfill and transfer material through their Roche lobes. They are rather common among the Milky Way’s field stellar population. In the solar neighborhood and the Galactic bulge, their population density is approximately 0.2%. In the Galactic disk it is somewhat lower, on average, $\sim 0.1\%$ (Rucinski 2006). CBs can be classified as early- and late-type systems; late-type CBs are also known as W Ursae Majoris (W UMa) systems. Observational evidence suggests that both binary components have very similar temperatures although their masses differ, a conundrum known as Kuiper’s paradox (Kuiper 1941). As a solution to this paradox, Lucy (1968) proposed convective common-envelope evolution as the key underlying physical scenario of CB theory. Our modern view is that CBs have most likely been formed through loss of angular momentum (Stępień 2006; Yıldız & Doğan 2013).

1.1. W Ursae Majoris systems

The late-type, low-mass W UMa variables are, in essence, ‘overcontact’ binary systems. Both of their binary components usually rotate rapidly, characterized by periods in the range from $P = 0.2$ days to $P = 1.0$ day. One can indeed easily obtain complete, high-quality W UMa light curves in just a few nights of observing time on relatively small telescopes. In this contribution, we present such observations of the six W UMa binary systems that reside in the old open cluster (OC) NGC 188.

As highlighted above, W UMa systems are common in both OCs and the Galactic field. This implies that they have great potential as potential distance indicators. Indeed, approximately 0.1% of the F–K-type Galactic field dwarfs are late-type CBs (Duerbeck 1984), while in OCs their frequency may as high as $\sim 0.4\%$ (Rucinski 1994). If we could establish a reliable (orbital) period–luminosity relation (PLR) for such W UMa systems, they might potentially be employed to adopt a similarly important role as the often used Cepheids or RR Lyrae variables in the context of measuring the distances to old structures in the Milky Way. We note that while distances to individual W UMa systems cannot be derived to the same level of accuracy as those resulting from Cepheid analysis, the high CB frequency in old stellar populations could potentially allow us to overcome this disadvantage.

1.2. NGC 188

NGC 188 is located at a distance of ~ 2 kpc. It contains a significant number of late-type CBs. Of these, seven W UMas near the cluster’s center were first found by Hoffmeister (1964) and Kaluzny & Shara (1987). Subsequently, Zhang et al. (2002, 2004) surveyed approximately 1 deg^2 around the center, yielding a CB haul of 16 W UMa systems. Branly et al. (1996) then used the Wilson–Devinney code to calculate light-curve solutions for five of the central W UMas and offered a discussion of the average W UMa distance compared with that to the cluster as a whole. Liu et al. (2011) and Zhu et al. (2014) published orbital solutions for EQ Cep, ER Cep, and V371 Cep, and for EP Cep, ES Cep, and V369 Cep, respectively.

We observed NGC 188 over a continuous period of more than 2 months using the 50 cm Binocular Network telescope (50BiN; Deng et al. 2013) at the Delingha Station (Qinghai Province, China) of Purple Mountain Observatory (Chinese Academy of Sciences). We obtained simultaneous time-series light-curve observations based on an unprecedented number of 2700 frames, representing an effective observing time of 44 hr. Details of the observations are included in Chen et al. (2016a). The telescope’s field of view, $20 \times 20 \text{ arcmin}^2$, is adequate to cover the cluster’s central region.

To only select genuine cluster members, we performed detailed radial-velocity and proper-motion analyses (Chen et al. 2016a). We eventually concluded that of our total sample of 914 stars, 532 stars are probable cluster members. The latter delineate an obvious cluster sequence in the color–magnitude diagram down to $V = 18$ mag. We used the Dartmouth stellar evolutionary isochrones (Dotter et al. 2008) to ascertain the nature of the cluster members, adopting an age of 6 Gyr and solar metallicity. We derived a distance modulus $(m - M)_V^0 = 11.35 \pm 0.10$ mag and a reddening of $E(V - R) = 0.062 \pm 0.002$ mag.

1.3. Distance determination

Rucinski (2006) published a simple $M_V = M_V(\log P)$ calibration, i.e. $M_V = (-1.5 \pm 0.8) - (12.0 \pm 2.0) \log P$, $\sigma = 0.29$ mag, based on his observations of 21 W UMa systems with good *Hipparcos* parallaxes and All Sky Automated Survey (ASAS) V-band photometry (maximum magnitudes). In Chen et al. (2016a), we established the equivalent relationship using our own (50BiN) V-band data, combined with the independently determined OC distance and the cluster’s average extinction.

We obtained accurate light-curve solutions for six W UMas of the NGC 188 variables. We used these to estimate the CBs’ physical parameters, including their mass ratios and the components’ relative radii. We subsequently estimated the distance modulus to the W UMa systems as a whole, independently of the cluster distance. W UMas can be used to derive distance moduli with an accuracy of often significantly better than 0.2 mag. For this aspect of our distance-modulus analysis, we excluded ER Cep given its low cluster-membership probability; in addition, we suspect its nature as an eclipsing binary-type system. For the remaining five W UMas—specifically, EP Cep, EQ Cep, ES Cep, V369 Cep, and V370 Cep—we obtained a combined distance modulus of $(m - M)_V^0 = 11.317 \pm 0.119$ mag. This value is indeed comparable to the result from our isochrone fits, $(m - M)_V^0 = 11.35 \pm 0.10$ mag, and also with previous results from the literature. The accuracy resulting from our new analysis is much better than that from application of the previously well-established empirical parametric approximation.

To carefully check our results for the cluster as a whole and the specific applicability of W UMas as distance tracer, we applied it to the OC Berkeley 39. Based on four of the latter cluster’s W UMas, we derived a distance modulus of $(m - M)_V^0 = 13.09 \pm 0.23$ mag. This is also in accordance with literature results. Thus, W UMas as potential distance tracers have indeed significant advantages for the most poorly studied clusters. Based on our initial analysis, we found that five of our NGC 188 W UMa systems obey the overall W UMa PLR. Armed with the latter, we were hopeful that W UMas could indeed play an important role in measuring distances and to map Galactic structures on more ambitious scales than done to date.

2. Period–luminosity relations

Although CBs are of order seven magnitudes fainter than the often used Cepheid variables, within the same distance range their number is three orders of magnitude larger. Cepheids trace young ($\lesssim 20$ Myr-old) features; CBs are instead found in 0.5–10 Gyr-old stellar populations. Although RR Lyrae stars are also members of structures older than 1–2 Gyr, very few of the latter variables have been found in either open clusters (OCs) or the solar neighborhood.

Since Eggen (1967)’s seminal work, these considerations and observations have triggered a number of attempts at using CB period–luminosity–color (PLC) relations to determine distances to such old structures. Rucinski & Duerbeck (1997) employed observations of 40 W UMa-type CBs characterized by *Hipparcos* parallaxes with an accuracy in the corresponding distance moduli of $\epsilon_M < 0.5$ mag to improve their PLC relation. Subsequently, Rucinski (2006) derived a luminosity function composed of CBs sourced from the ASAS data. He then explored the viability of a V-band PLR. However, his ‘PLR’ exhibited only a weak correlation and was affected by large uncertainties and significant scatter.

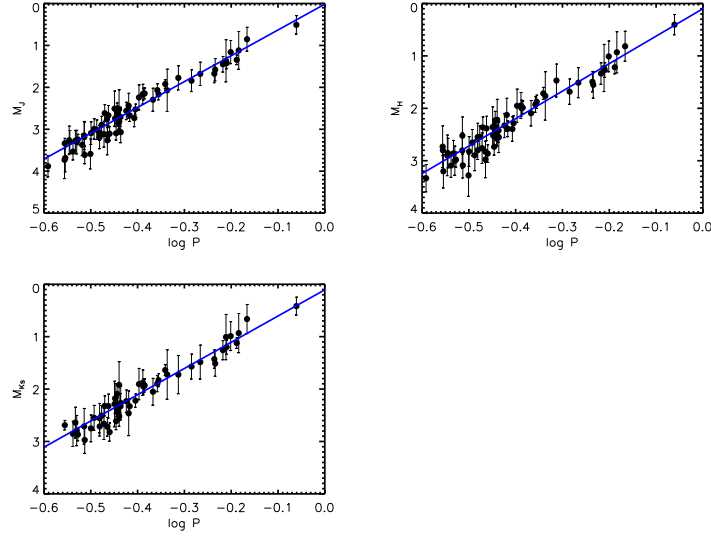


Figure 1. Our new JHK_s CB PLRs (magnitudes as a function of period, in days), adapted from Chen et al. (2016b).

We collected CBs in OCs and CBs with accurate *Hipparcos* parallaxes (Chen et al. 2016b), aiming at establishing more reliable PLRs. Our full sample contains 6090 CBs from the General Catalog of Variable Stars and the ASAS. Our corresponding OC sample contains 2167 OCs. We made a special effort to exclude foreground and background CBs, requiring that (i) any suitable CB must be located inside the core radius of its host OC; (ii) the CB’s proper motion must be located within the 2σ distribution of that of its host OC; and (iii) the CB’s age must be similar to that of its host OC, i.e. $\Delta \log(t \text{ yr}^{-1}) < 0.3$. Our final sample selection consisted of 42 high-probability OC CBs. Combined with four nearby moving-group CBs and 20 W UMa-type CBs with accurate *Hipparcos* parallaxes, we hence used a sample of 66 CBs to determine the JHK_s PLRs, i.e.,

$$M_{J_{\max}}^{\text{late}} = (-6.15 \pm 0.13) \log P + (-0.03 \pm 0.05), \sigma_J = 0.09, (\log P < -0.25);$$

$$M_{J_{\max}}^{\text{early}} = (-5.04 \pm 0.13) \log P + (0.29 \pm 0.05), \sigma_J = 0.09, (\log P > -0.25);$$

$$M_{H_{\max}} = (-5.22 \pm 0.12) \log P + (0.12 \pm 0.05), \sigma_H = 0.08;$$

$$M_{K_{s,\max}} = (-4.98 \pm 0.12) \log P + (0.13 \pm 0.04), \sigma_K = 0.08.$$

These PLRs result in distances that are as accurate as those derived from the JHK_s Cepheid PLRs (scatter $\sigma < 0.10$ mag): see Fig. 1. In fact, these relations are the first PLRs for early-type CBs thus far established at near-infrared wavelengths. In order to verify the accuracy of our PLRs, we carefully investigated the CBs’ period–color relations. The latter can be employed to get rid of unreliable CBs. Near-infrared PLRs are more accurate and significantly less sensitive to extinction and metallicity variations than V-band PLRs.

Combining the JHK_s PLRs, we derived the distances to our sample of 6090 CBs. The resulting accuracy is high: 90% of our sample CBs have distance errors of less than

5%, and 95% have distance uncertainties of less than 10%. The remaining 5% may be CBs associated with poor-quality photometry, variables affected by high or complicated differential extinction, or objects that could have been misidentified as CBs, e.g. semi-detached binaries and—for small amplitudes—RR Lyrae and ellipsoidal binaries.

2.1. Application to the Large Magellanic Cloud

Graczyk et al. (2011) published a catalog of 26,121 eclipsing binaries in the Large Magellanic Cloud (LMC), which had been identified based on visual inspection of the Optical Gravitational Lensing Experiment III catalog. Their 1048 type-EC eclipsing binaries are CBs, although they only included CBs with long periods ($\log P > -0.2$ [days]). To select CBs that can be used as reliable distance tracers, we adopted our period–color selection and imposed period limits of $-0.13 < \log P < 0.2$. Here, the upper limit is at the long-period end of the CB distribution and the lower limit is the magnitude limit used for detecting LMC CBs.

This resulted in a total sample of 102 LMC CBs and a distance modulus of $(m - M_V)_0 = 18.41 \pm 0.20$ mag. This is first distance to the LMC based on CBs. It is entirely consistent with the current best LMC distance modulus (de Grijs et al. 2014), $(m - M)_0 = 18.49 \pm 0.09$ mag.

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